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# Flow-Visualization Techniques Used at High Speed by Configuration Aerodynamics Wind-Tunnel-Test Team

*Edited by*  
*John E. Lamar*  
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April 2001

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National Aeronautics and  
Space Administration

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## **Nomenclature**

BSWT	Boeing Supersonic Wind Tunnel
BTWT	Boeing Transonic Wind Tunnel
CCD	charged coupled device
CFD	computational fluid dynamics
$C_p$	pressure coefficient
ESP	electronic scanning pressure
HSR	High Speed Research
IR	infrared
LE	leading edge
M	Mach number
MSDS	Material Safety Data Sheet
NCV	nonlinear cruise validation
NTF	National Transonic Facility at Langley Research Center
PC	personal computer
PSP	pressure sensitive paint
Re	Reynolds number
rms	root mean square
SGI	Silicon Graphics, Inc.
TSP	temperature sensitive paint
UPWT	Langley Unitary Plan Wind Tunnel
UV	ultraviolet
VIAS	video image acquisition system
16FTT	Langley 16-Foot Transonic Tunnel





# Abstract

*This paper summarizes a variety of optically based flow-visualization techniques used for high-speed research by the Configuration Aerodynamics Wind-Tunnel-Test Team of the High-Speed Research Program during its tenure. The work of other national experts is included for completeness. Details of each technique with applications and status in various national wind tunnels are given.*

## 1. Introduction

During the high-speed, wind-tunnel test phase of the High-Speed Research Program, a variety of optically based, flow-visualization techniques were used by the Configuration Aerodynamics Wind-Tunnel-Test Team to determine flow features on and around the model in both a qualitative and quantitative sense. Selection of an appropriate technique was dependent on its availability at the test facility and the information required. The techniques used are divided into three groups which highlight the type of information needed: (1) surface flow, (2) surface properties, and (3) off-surface features. In particular, techniques employed to obtain (1) surface-flow details were ultraviolet (UV) oil, colored oil, and minitufts; (2) surface properties were oil film interferometry, infrared (IR) thermography, sublimation, pressure sensitive paint (PSP), and temperature sensitive paint (TSP); and (3) off-surface features were laser vapor screen, schlieren, and shadowgraph. A subset of these techniques was available at all facilities where tests were conducted. Many of these techniques have been documented in reference 1 or are extensions of established practices.

This paper was written with three main purposes in mind: (1) to document those techniques used by the team through definition and highlighting the expected results; (2) to provide details for the use of each technique and a record of its operational status or planned implementation for the test facilities of interest to the team; and (3) to serve as a handy optical technique and facility reference for those researchers planning to acquire similar data. When this report was commissioned, the contributors identified were either members of the team or other national experts and their names appear in the sections they authored. The eleven techniques are presented in the order given in this section.

## 2. Definitions, Expected Results, and Details of Use in Facility Implementation

### 2.1. Surface-Flow Techniques

#### 2.1.1. Ultraviolet Oil

*Kevin M. Mejia  
Boeing HSCT High Speed Aerodynamics*

*Gary E. Erickson and Clifford J. Obara  
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The UV oil (ref. 1) is a qualitative surface technique and uses a phosphorescent-dye-enriched oil, in either thin-film or dot form, that upon excitation with UV illumination allows the visualization of a surface flow pattern over the model. This technique is used for determining surface flow patterns and has been employed by the Configuration Aerodynamics Wind-Tunnel-Test Team in a variety of industry and NASA wind tunnels.

##### *2.1.1.1. Application in Boeing Supersonic Wind Tunnel*

The procedures for obtaining UV oil photographs in BSWT are given in this section.

Equipment used:

L100 industrial grade oil

H15 oil

UV phosphorescent dye (Reveal A680 plus, leak detection additive)

2000-W flash unit with "black" UV glass

BG39 (Scott, blue glass) and E2 (Ratten, yellow glass) camera lens filters

UV oil mixture:

For  $Re = 9 \times 10^6/\text{ft}$ —

Mix 4 to 6 drops of dye with 50–50-percent mixture of L100 and H15 oil

For  $Re = 12 \times 10^6/\text{ft}$  and  $14 \times 10^6/\text{ft}$ —

Mix 4 to 6 drops of dye into 100-percent mixture of L100 oil

Application process:

Apply UV oil directly onto bare metal wing surface using quality paint brush

Run blowdown tunnel for extended time at that  $Re$

Photography process:

Snap images immediately after blowdown tunnel run

Take pictures directly above upper or lower surface focusing on inboard and outboard wing sections and LE break regions; make certain that transition location can be clearly seen

Roll model wings vertically just prior to snapping image to facilitate process

#### *2.1.1.2. Application in Langley Unitary Plan Wind Tunnel*

An ultraviolet oil technique was used in the low Mach number and high Mach number test sections in UPWT to visualize the surface streamline patterns about wings, bodies, and other aerodynamic shapes at supersonic speeds. A uniform coating of a mixture of RPM Day-Glo yellow fluorescent liquid and W140 gear oil was painted onto the bare metal model surface area. The model roll angle orientation was upright or  $\pm 90^\circ$ , depending on the region of interest. The base of the model was typically "plugged" with tissue and tape to prevent oil from migrating into the fuselage cavity and contaminating the internal instrumentation.

The UV oil was excited by several UV light sources which contained both continuous and 2000-W flash units. The surface flow patterns were documented with an array of externally mounted still and video cameras that were positioned inside the webbing of the test section sidewalls. The UV oil remained on the model surface in sufficient quantity at the desired test condition to allow several images to be acquired at three or four angles of attack. Imagery was accomplished with appropriate filters on the 70-mm Hasselblad still cameras and the high-resolution color and gray-scale digital cameras. Video streams were acquired from color and black-and-white cameras that could be connected to video recorders, PC-based video frame grabbers, and a separate video printer unit. The UPWT PSP system provides scientific-grade digital cameras connected to PC and SGI platforms to acquire and process high-resolution UV oil images. These images could be exported shortly after the flow-visualization run series to the World Wide Web site established for the ongoing test. An example of a digital UV oil image processed via the PSP system is shown in figure 1. A recent addition to the UPWT camera inventory is a high-resolution color digital unit that can be controlled remotely via a PC, which also provides the means of processing and exporting the images to remote customers.

#### *2.1.1.3. Application in Langley 16-Foot Transonic Tunnel*

The same technique used in the UPWT was used in the 16FTT at transonic speeds.

#### **2.1.2. Colored Oil**

*Kevin M. Mejia*

*Boeing HSCT High Speed Aerodynamics*

*Gelsomina Cappuccio*

*NASA Ames Research Center*

This qualitative surface technique uses dots of different colored oil to trace out the flow over the model surface. The colored-oil technique is used for observing surface flow features and was applied by the Configuration Aerodynamics Wind-Tunnel-Test Team in a number of wind tunnels. These include the BSWT, UPWT, and 16FTT. Application details follow.

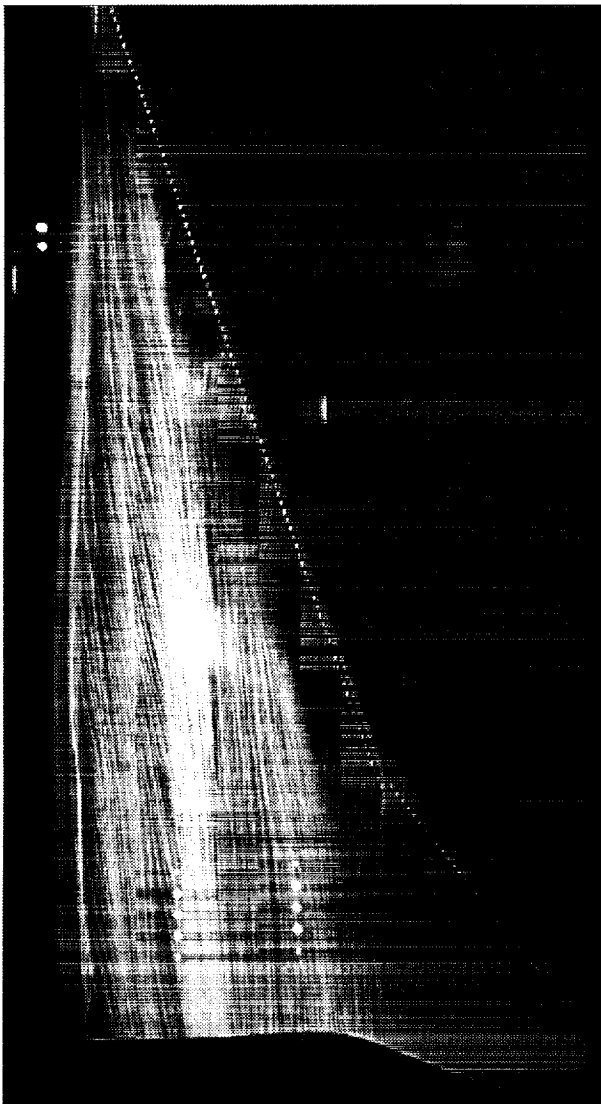


Figure 1. Example of UV oil image in UPWT.

#### 2.1.2.1. Application in Boeing Supersonic Wind Tunnel

The procedures for obtaining colored-oil-flow photographs in BSWT are given in this section.

##### Equipment used:

Linseed oil paint (white, yellow, blue, red)

W50 motor oil

Tempera paint

Plastic syringe needle

##### Oil mixture for supersonic application:

###### For dots—

Mix 2 tubes of oil paint (1.25 oz each), 4 heaping tbsp. of tempera powder, and 4 oz of W50 motor oil; mix in more motor oil if necessary until oil easily runs off mixing utensil

###### For base—

Use same mixture as for dots but add an additional 4 to 6 oz of oil (8 to 10 oz total)

##### Oil mixture for transonic application:

###### For dots—

Mix 2 tubes of oil paint, 4 heaping tbsp. of tempera powder, and 4 oz of W50 motor oil

###### For base—

To be determined

##### Application process:

Paint thin base coat of light-colored oil (white) over entire area of interest; base coat should be more viscous than colored-oil dots and be thin enough to spread easily onto wing (i.e., brush marks should disappear shortly after application)

Apply small (1/8-in-diameter) colored-oil dots in a densely packed pattern over the area of interest (1- by 1-in. matrix) by using a syringe needle. On forebody, space dots 2 in. streamwise

To run, set angle of attack and perform full blowdown tunnel run (drain tanks down to approximately 50 psi)

##### Photography process:

Capture initial and final condition of paint by using either a digital camera or a 35-mm single-lens reflex (SLR) camera

Issues for future:

Find mixture for oil dots to duplicate BSWT 628 flow-visualization images

Validate BTWT transonic mixture in BSWT transonic insert

#### *2.1.2.2. Application in Langley Unitary Plan Wind Tunnel*

The exact same technique used in BSWT was applied in UPWT.

#### *2.1.2.3. Application in Langley 16-Foot Transonic Tunnel*

The exact same technique used in BSWT was applied in 16FTT.

### **2.1.3. Fluorescent Minitufts**

*Kevin G. Peterson*

*Boeing HSCT High Speed Aerodynamics*

The fluorescent minituft technique (ref. 1) is qualitative and involves the illumination of UV fluorescent-filament tufts applied to the model surface. For a snapshot of the flow field—indicating both flow direction and the presence of separation—only a short duration of UV illumination is needed for the tufts to give off fluorescence, whereas for video a long-duration UV source is required.

#### *2.1.3.1. Application in Langley Unitary Plan Wind Tunnel*

The procedures for fluorescent minituft flow-visualization data obtained in UPWT are given in this section.

Method overview:

The fluorescent minituft flow-visualization method involves illumination of UV fluorescent-filament tufts applied to the model surface with high-intensity UV light for a short duration. Images taken during the tuft illumination provide a snapshot of the

surface flow field indicating both flow direction and the presence of separation.

Equipment used:

Boeing VIAS

PT4000 Norman power packs, strobe lights and UV filters, UV goggles

Cameras and UV filters

Sony medium-resolution CCD video camera (8 bits, 640 by 480 pixels)

Kodak DCS460 high-resolution digital camera (14 bits, 1024 by 1024 pixels)

Hasselblad still camera

UV monofilament treated with UV fluorescent dye

Carboset 526 polymer glue (requires MSDS) and acetone

Syringes and scalpels for application of minitufts

Adhesive mixture preparation:

Prepare syringe needles by cutting off sharp tip with a jeweler's file or by any other means which does not crimp the needle; also have dummy plugged needle ready (keep needle on syringe until application process begins)

Pour chemically pure acetone into container that will not contaminate it

Pull 5 cm<sup>3</sup> of acetone into syringe, turn vertically (needle up), and fill rest of syringe with air

Remove needle and replace with plugged (dummy) needle

Hold syringe vertically, with needle down, and gently pull out plunger being careful not to douse yourself with acetone

Pour in 1 cm<sup>3</sup> of glue crystals

Squirt in ≈0.2 cm<sup>3</sup> of Krylon paint; paint is used to eliminate fluorescence of tuft tail under glue, which may lead to misinterpretation of flow-visualization data

Gently insert end of plunger into syringe and turn vertically (plunger down)

Put working needle back on syringe and expel the remaining air

Replace working needle with dummy needle

Store for 1 day and rotate occasionally so paint mixes with solution

#### Minituft material selection:

Minituft material selection is driven by durability and tuft brightness. The Boeing tuft expert (James P. Crowder) indicated that nylon is better for exposure but is fragile, whereas polyester is more durable but provides for a less bright image. Therefore if adequate lighting and high-quality cameras are available, polyester is the natural choice because retufting part of the model is a task to be avoided. If lighting is critical and the number or duration of the required tuft runs is kept to a minimum, nylon should be considered.

Minituft application (on 1.675-percent nonlinear cruise validation model—one model from a stable of models used in HSR Program):

Clean surface of model to be applied with tufts to remove oil and other contaminants

Start at wingtips and lay minituft filament streamwise, from leading edge to trailing edge, taping at both ends as shown in figure 2; best to apply tufts to one surface (upper or lower) at a time; keeping the filament fairly loose to follow the contours of surface; filament should not stand

off of surface at any point because more difficult to apply glue dots; for 1.675-percent NCV model, a spanwise spacing of 0.38 in. was chosen

Once filament application is complete, take syringe with prepared adhesive solution and shake vigorously to ensure that paint is properly mixed

With paper towels handy, replace dummy needle with working needle and begin glue dot application process; getting an appropriate adhesive flow rate is a bit tricky; best if an ample amount of air is drawn into the syringe and plunger gently depressed; best method of keeping glue dot height to a minimum is to draw needle tip gently across filament (normal to the direction of filament travel), which seems to create a wide but very low profile glue dot; for 1.675-percent NCV, a tuft length of 0.038 in. is desirable

Starting at leading edge, place dots (fig. 3) at desired intervals down length of one filament line; best not to work over filament line on which glue dots have already been applied; working from inboard to outboard is best choice; if filament does stand off of surface at any point, either add a small piece of tape or hold it against surface while adhesive is being applied and let cure for a couple of minutes

Once dot application is complete, begin cutting tufts; with very sharp scalpel, GENTLY slice each tuft just ahead of glue dot for following tuft as shown in figure 4; each person has a method of cutting the tufts; needless to say the surface must not be scratched



Figure 2. Minituft layout pattern.



Figure 3. Application of glue dots.

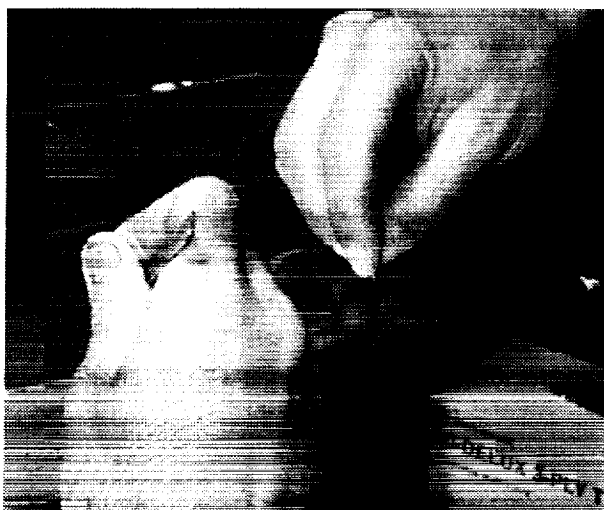


Figure 4. Cutting of minitufts.

Remove tape from leading and trailing edges and move on to next surface

After all surfaces are prepared, store remaining adhesive; any work done on model will require reapplication of some of tufts

Figure 5 shows three views of the minitufted NCV as a visual reference of the prepared model. Standard practice is to provide as much UV light as possible and close the aperture of the camera if overexposure is a problem. The constant-source UV lights which were available for Test 1703 were borrowed from a PSP system and were used primarily for UV-oil flow-visualization runs.

#### Equipment setup:

##### Light sources—

Both constant-UV and flashlamp light sources were successfully used during the course of UPWT Test 1703. Flashlamps provide a more instantaneous view of the flow field, whereas the constant-light sources provide a time-averaged image. For very steady flows, the constant-source lights may be able to provide adequate data. For most situations, it is highly recommended that flashlamps be applied. However, constant-source lights are invaluable because they allow the test participants to view the tufts during the course of the run whereas flashlamps do not.



Figure 5. Minitufted NCV model.

The Boeing VIAS system for minituft flow visualization uses flashlamp systems with UV transmitting filters which are triggered by the VIAS computer. For UPWT Test 1703, 2000 W/sec flashlamps were driven by Norton PT-4000 Power Packs. The number of lamps required depends on the area to be illuminated and the wind tunnel. The window material

must be transparent to the UV light. Rohm and Haas Plexiglas acrylic is moderately transparent and ordinary plate glass is usually more than sufficient. Because the fluorescent tuft visualization process involves illuminating the model in the UV spectrum and imaging the tufts in the visible spectrum, the filters used to block the reflected light virtually eliminated the problem of model glare.

#### Cameras—

Three different cameras were used with varying degrees of success in obtaining minituft images: medium-resolution Sony CCD video cameras, high-resolution Kodak DCS460 digital camera, and Hasselblad still cameras. Each camera type used had its advantages and disadvantages. The medium-resolution Sony cameras provided instantaneous access to the images but provided lower image quality. The high-resolution DCS460 images were of excellent quality, but the image transfer and viewing process made real time or even during-run viewing of the images impossible. The Hasselblad images were of the highest quality but required several days of turnaround time. Sample images from the medium-resolution CCD camera and Hasselblad cameras are presented in figures 6 and 7.

#### 2.1.3.2. General Comments on Minituft Testing

Although minituft testing has the potential to provide a great deal of information about the surface flow field, it requires significant equipment and time investment. In order to minimize the impact of the minituft runs on the overall test schedule, it is highly recommended that a system be used (computer, power packs, lights, and cameras) which has been successfully integrated prior to the test. Having personnel familiar with the intricacies of the system and familiar with minituft application techniques is also highly desirable. The Boeing VIAS system used during Test 1703 was a bare-bones system pieced together from available equipment because the primary systems were committed to other tests. If enough lead time is provided, a system with high-resolution cameras, a powerful computer with significant data storage

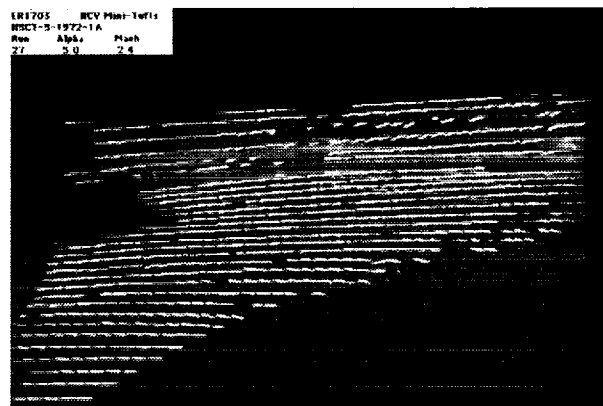


Figure 6. Medium-resolution Sony CCD camera image of upper wing-body obtained by VIAS computer.

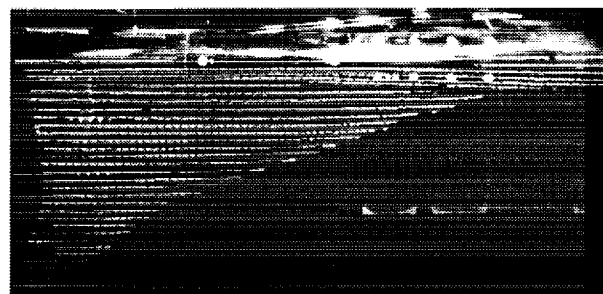


Figure 7. Hasselblad still image of upper wing surface.

capability, strobe lights, and power packs which have been successfully integrated should be available. It is highly recommended that either the Boeing VIAS or similar NASA system be used during future minituft testing. This usage has the potential of dramatically reducing the frustration and head scratching associated with attempting to integrate and debug a new system on the fly.

## 2.2. Surface Property Techniques

### 2.2.1. Oil Film Interferometry

*Robert A. Kennelly, Jr.*  
NASA Ames Research Center

#### 2.2.1.1. Method Overview

Oil film interferometry (refs. 2 to 6) is both a qualitative and quantitative technique for determining skin friction. Interference fringes are produced when a

film of transparent oil, thinned by the action of the fluid passing over the test article, is illuminated by a monochromatic light source. With some simplifying assumptions, the spacing of the fringes is proportional to surface shear in the direction perpendicular to the leading edge of the oil film. As a qualitative tool, the technique may be used to observe boundary-layer transition.

Oil film interferometry is a relatively nonintrusive technique for measuring skin friction on models and is discussed in references 2 to 6. No special model preparation is needed, although an optically smooth surface is required. This condition can be inexpensively produced by a thin layer of Du Pont Mylar polyester film temporarily glued to the model. Dedicated runs at constant wind-tunnel conditions are required to obtain the flow-visualization images for analysis. A line or dot of transparent silicone oil (Dow Corning DC-200 Fluid) gradually thins under the influence of surface shear. Under suitable assumptions, the slope of the oil surface at the leading edge of the oil is simply related to the component of local skin friction perpendicular to the edge. Optical interferometry provides a sensitive probe for measuring the wedge angle of the film.

The oil is nontoxic and has a low vapor pressure. It is available in a wide range of kinematic viscosities from 10 to 30 000 cSt (5 percent, at 25°C). We found it necessary to calibrate the oil viscosity at several temperatures in the range of interest because there is some evidence that the viscosity drifts slowly over a period of months. (Other relevant properties such as density and index of refraction still need to be investigated.)

The interference fringes were easily seen by eye and were not too difficult to photograph, although a tripod was needed to permit the long exposures (typically 0.5 to 2.0 sec), and small lens openings were required for adequate depth of field.

Wind-tunnel run times must be long enough to render negligible the effects of startup and shutdown transients and the oil viscosity chosen to produce a convenient fringe spacing in that length of time. The demonstration test for the HSR program used run lengths of 30 min of "on condition," with startup and shutdown each taking about 5–10 min. Oil viscosity was nominally 10 000 cSt, and total temperature was

125°F. The resulting fringe spacings were on the order of 1.8 mm (laminar) and 3.0 mm (turbulent) and could be measured from a photograph to within a few percent with a caliper.

Constancy of the local skin friction coefficient was assumed. Skin friction coefficient is difficult to assess directly, but this source of error can be brought under control (for reasonable flows) by varying the run time—for a sufficiently long run, the effect of nonconstant skin friction coefficient should become negligible.

#### *2.2.1.2. Application in Langley Unitary Plan Wind Tunnel*

Figure 8 shows the model installed in one test section of the UPWT.

The vertical orientation of the wings proved to be advantageous during post-run photography of the fringe images, permitting near normal illumination and viewing angles. Three patches of black Top Flite MonoKote plastic are visible on the upper surface of the left wing.

The Iwasaki reflector lamps in the figure are those used for obtaining the interference images, but in actual use their light is bounced off a large white card to provide a uniform, diffuse source against whose reflection in the Mylar film the interference fringes are visible. The lamps are 160-W, self-ballasted, high-intensity discharge mercury type, with a strong spectral peak at a wavelength of 546.1 nm (green). This peak is isolated by photographing through a

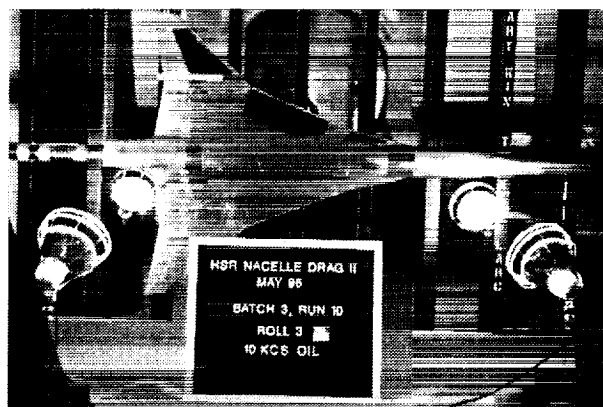


Figure 8. Model installed in UPWT.



green filter. Various filters have been used, ranging from simple dyed photographic filters to dichroic process filters to custom-made interference filters. Although more expensive, the latter is preferred.

Figure 9 shows an example of the results obtained on an HSR model.

Interference fringes are clearly visible, having formed downstream of three spanwise oil lines. The boundary-layer trip consisted of epoxy dots large enough to provoke transition, and the middle one third had no trip applied. A jump in fringe spacing from broadly spaced fringes downstream of the dots to more narrowly spaced fringes in the presumably laminar region is clearly visible.

The zigzag pattern in the fringes near the leading edge is significant. A detailed look at the dot wakes in a low-speed facility revealed patterns that were even more complex. The oscillations die out as the distance from the oil line to the transition strip increases.

The streaks in the oil suggest surface streamlines, but these have sometimes been misleading in other work. The path of an oil droplet on the dry Mylar film surface is not necessarily a reliable indication; we suggest another technique such as UV fluorescent oil flow and a completely wetted surface for such visualization.

### 2.2.2. IR Thermography

*Kevin M. Mejia*  
*Boeing HSCT High Speed Aerodynamics*

IR thermography (ref. 1) is a qualitative surface technique and uses the principle that laminar and turbulent flows have different surface heat-transfer rates during wind-tunnel testing. The IR illumination exposes these regions on the surface with different rates in order to facilitate, in a global sense, the identification of the dominant flows and where boundary-layer transition occurs. This technique has been employed in a variety of wind tunnels; however, the Configuration Aerodynamics Wind-Tunnel-Test Team only used it in BSWT. The specific application practices used in that tunnel are detailed.



Figure 9. Closeup of HSR model showing typical results.

#### 2.2.2.1. Application in Boeing Supersonic Wind Tunnel

The procedures for IR transition photographs obtained in BSWT are given in this section.

Equipment used:

Inframetrics 760 IR camera

White Krylon (spray paint)

Preparation process:

Apply thin base coat of light white Krylon paint over entire area of interest and allow to dry; use backside of black 100 grit sandpaper to smooth paint (base coat should be smooth to the touch and "feel" only slightly rougher than bare model surface)

Heat outboard panel with heat gun until too hot to touch

Set camera temperature sensitivity range to 20°C

Center IR camera temperature scale by using heated wingtip prior to running (10° to 30°C is good starting point for hot outboard wing)

Run and photography process:

For  $M = 2.4$ ,  $Re = 9 \times 10^6/ft$ , and wingtip—

When tunnel starts up, have wingtip initially off scale (30+°C); let wing cool down approximately 3–5 sec after model gets on condition

before adjusting temperature scale to allow wing temperatures to fall within temperature scale

As run progresses, adjust camera temperature scale by approximately  $-1^{\circ}\text{C}/\text{sec}$  to keep as much of laminar region as possible visible in monitor; at end of blowdown tunnel run, low end of scale should be at  $-10^{\circ}$  to  $-15^{\circ}\text{C}$

For  $M = 2.4$ ,  $Re = 12 \times 10^6/\text{ft}$ , and wingtip—

Set initial temperature scale to  $15^{\circ}$  to  $35^{\circ}\text{C}$

Adjust temperature scale by  $-1.5^{\circ}\text{C}/\text{sec}$

For  $M = 2.4$ ,  $Re = 14 \times 10^6/\text{ft}$ , and wingtip—

Set initial temperature scale to  $20^{\circ}$  to  $40^{\circ}\text{C}$

Adjust temperature scale by  $-2^{\circ}\text{C}/\text{sec}$

Issues for future:

Determine technique for transonic Mach numbers when using transonic insert

Determine process for forebody and inboard wing laminar runs—thick sections are out of easy viewing range because viewing portal in BSWT allows only limited visibility of model; portal could be rotated within circular window blank to view inboard wing, but nose viewing would be problematic; angling of camera could also help

Determine effect on boundary layer of preheating outboard wing panel: Does artificial heating used to produce IR imaging cause premature boundary-layer transition relative to standard testing conditions? What adjustments should be made to calculate laminar run drag effect?

### 2.2.3. Sublimation

*Kevin M. Mejia*

*Boeing HSCT High Speed Aerodynamics*

*Aga Goodsell*

*NASA Ames Research Center*

Sublimation (refs. 1 and 7) is another qualitative surface technique and is based on the same principle

as that of the IR thermography. However, this surface application uses a chemical which sublimates at different rates depending on whether the flow is laminar or turbulent. Hence, it can also be used quantitatively to measure the spatial location of boundary-layer transition. This technique was employed by the Configuration Aerodynamics Wind-Tunnel-Test Team in a variety of industry and NASA wind tunnels.

#### 2.2.3.1. Application in Boeing Supersonic Wind Tunnel

The procedures for obtaining sublimation photographs in BSWT are presented in this section.

Equipment used:

Naphthalene

Allied Chemical Genesolve solvent

Air sprayer with supply line set to 30 psi

Portable spray booth

Two fans

Sublimation mixture:

Mix until Genesolve solvent is saturated with naphthalene material, usually 8 parts Genesolve to 1 part naphthalene by volume

Application process:

Erect spray tent around model, direct fans to blow air out of diffuser (make sure diffuser "garage" door is open), open bay door to outside, dress technician appropriately, that is, protective clothing and respirator

Apply material on lower surface first

Run blowdown tunnel for extended wind-on time; watch to make sure that sufficient material remains for pictures; adjust run time (longer or shorter) as necessary

For  $Re = 9 \times 10^6/\text{ft}$ —

Rotate model  $90^{\circ}$  so that wings are vertical for application

Clean entire surface to be sprayed with Genesolve solvent; if model has been recently run, warm surface to room temperature with a heat gun

Apply sublimation material directly to bare metal holding spray nozzle perpendicular to model surface and approximately 8–10 in. away; make sure that entire inboard leading edge is covered by sublimation material; to easily achieve this hold spray gun at 45° angle to leading edge; do three slow, even passes over entire wing (leading-edge highlight to trailing edge), paying close attention to applying an even coat; do an additional three passes on inboard wing segment only

For  $Re = 12 \times 10^6/\text{ft}$  and  $14 \times 10^6/\text{ft}$ —

Apply sublimation material as instructed for  $Re = 9 \times 10^6/\text{ft}$ ; do only two slow, even passes over entire wing (leading-edge highlight to trailing edge), paying close attention to applying even coat; do additional three passes on inboard wing segment only

#### Photography process:

Snap images immediately after blowdown tunnel run

Take pictures directly above upper or lower surface focusing on inboard and outboard wing sections and the LE break regions. Make certain that transition location can be clearly seen

Roll model wings vertically to facilitate the process

Photograph some zoom images with ruler in place

Measure laminar run at several locations with ruler and hand sketch transition location with measurements

#### Issues for future:

Determine technique for transonic Mach numbers in BSWT

Changing the sublimation chemicals is needed at higher Mach numbers (see ref. 7)

#### 2.2.3.2. Application in Langley Unitary Plan Wind Tunnel

##### Equipment used:

Fluorene

Allied Chemical Genesolve solvent

Air sprayer with supply line set to 30 psi

Portable spray booth

Two fans for ventilation

Two Hasselblad cameras, one per side of test section

40-mm wide-angle lens to capture entire wing

Four lights, two per side of test section

70-mm, monochrome, ISO 400, Tri-X film without special processing

##### Test setup procedure:

Mount two video cameras, one on each side of the test section, and use hand-held camcorder for closeup shots during run

With stencil and spray paint, paint trip dot height, run number, and date on both upper and lower surfaces in regions without sublimation material

Before spraying sublimation mixture on model, leave a few isolated dots on either side of the wing so that transition wedges are clearly visible; depending on wing sweep, two or three dots may be removed on either side of isolated dot; for HSCT tests, three dots were removed on highly swept inboard wing and two dots outboard

##### Sublimation mixture and procedure:

Mixture is saturated solution of fluorene in Genesolve (1:8 parts by volume) passed through a coarse filter; Binks Model 2001 spray gun was used to apply the sublimation material; this spray gun uses compressed air (can containing solution is not pressurized) to produce a high-velocity jet of air and sublimation solution is siphoned into air stream by suction; full application (both surfaces) required approximately 1.5 qt of mixture for Reynolds number of  $4 \times 10^6$

For consistency of application, spray material on warm model, either after having run model or by heating model with heat lamps overnight; to maintain a constant coating, spray many light coatings while frequently alternating between upper and lower surfaces

#### Photography process:

f-stop was f/11 and shutter speed was 1/15 sec for still camera with high intensity floodlamps; with two 400-W-sec strobes, exposure was f/11 at 1/125 sec

Camera should be focused with model pitched in running position

Two Polaroid cameras needed to check exposure settings for Hasselblad cameras

Take Polaroid pictures to determine proper exposure settings

Before start of run, take two Hasselblad pictures to ensure that camera is ready for first data photograph

Take picture with camera lens covered to signify true beginning of run

Turn on videotapes so that entire sublimation process can be documented

After tunnel start, set block to obtain desired free-stream Mach number

Pitch strut was to desired angle of attack

Start pictures at 1-min intervals when nearly on condition (Note: This is good time to verify that both cameras are advancing properly)

Run tunnel until most of sublimation material on upper and lower surfaces is scrubbed off in turbulent region. (Note: A data point is recorded simultaneously with each picture so that tunnel conditions are recorded during run but data not corrected for side flow angularity)

#### Issues for future:

40-mm lens may be too wide; using a lens that can zoom more closely onto the areas of interest may be preferable

Problems with lighting need to be improved; because webs on outside of test section, lighting is difficult to control, causing glare in bare spots on model, which makes analysis somewhat more difficult in those areas

Try using UV illumination, with suitable filtration on camera lens, to see if recording just fluorescence of fluorene material under UV can reduce glare

#### *2.2.3.3. Application in Langley 16-Foot Transonic Tunnel*

Development work was done in 16FTT during Test 508 using much of what was learned in the UPWT.

#### *2.2.3.4. Application in National Transonic Facility*

This same technique has been used on occasion in NTF.

#### **2.2.4. Pressure Sensitive Paint**

*James H. Bell*  
*NASA Ames Research Center*

*Clifford J. Obara and Gary E. Erickson*  
*NASA Langley Research Center*

PSP (refs. 8 and 9) is a quantitative surface technique and takes advantage of the chemistry of a special fluorescent paint that varies in brightness with air pressure (partial pressure of oxygen). The paint, when applied to a model and illuminated with either UV or blue lights, is excited under both wind-on and wind-off test conditions. These paint images on the model are recorded by using specialized video cameras during testing. After processing, the images show quantitative pressure data and can be mapped onto a model surface geometry for comparison with CFD or calculation of model loads.

##### *2.2.4.1. General Procedure*

First paint model with PSP paint; illuminate with either UV or blue lights to excite paint

Images of model recorded during test by using specialized video cameras; after processing, images show quantitative pressure data and can be mapped onto model surface geometry for comparison with CFD or calculation of model loads (see refs. 8 and 9 for additional details and documented applications); accuracy varies from 0.02 in  $C_p$  at transonic and supersonic speeds to 0.15 at low subsonic speeds

Problems with this technique include sensitivity to temperature variations, large model downtime for paint application, and low data rates, especially in low-speed wind tunnels

PSP capability for selected government facilities is presented in this section in the format of the following defined items:

Status:

Status is "operational" if PSP has been used in the facility previously, or "implementation" if PSP work is planned but has not been done previously. This category includes tunnels in which PSP was used before the tunnel was refurbished.

Downtime for PSP application:

This is the number of shifts the tunnel cannot be run because of PSP application. Actual schedule impact could be lower because paint application could be performed over weekend or off shift. Downtime for PSP removal is typically 0.5 shift.

Data acquisition rate:

This is the time per data point. The total data acquisition time is composed of two components—actual wind-on time of image recording and required wind-off calibration—with the latter being a fraction of former. The calibration time is typically larger for low-speed wind tunnels because of the lower PSP signal-to-noise ratio at low speeds. Selected reduced data are typically available 1–2 hr after data acquisition, with the complete reduced data set available within 2 wk to 1 mo, depending on test complexity and priority

Typical PSP accuracy in  $C_p$ :

This is the rms difference between pressure tap data and PSP data at the tap locations.

Notes:

These comments are tunnel specific.

*2.2.4.2. Application in Ames 12 ft Pressure Wind Tunnel*

Status:

Operational

Downtime for PSP application:

2 shifts

Data acquisition rate:

1–3 min/data point + 100 percent extra time for wind-off images

Typical PSP accuracy in  $C_p$ :

0.2 for  $M = 0.2$  at 1–2 atm; 0.3 for  $M = 0.2$  at 3–6 atm

Notes:

PSP applications in 12 ft tunnel tend to involve large, complex models for which painting is difficult and require a large number of cameras to get all the desired views. In the past, this difficulty has led to longer than anticipated setup times and lower than anticipated data rates. PSP flow intrusiveness is a concern for subsonic high-lift models but has not been observed on delta wing models. Optical access is very good for semispan and vertically mounted models and for the upper surface of horizontal models. Optical access for the lower surface of horizontally mounted models is fair to poor.

#### 2.2.4.3. Application in Ames 7 × 10 ft Wind Tunnel

Status:

Operational

Downtime for PSP application:

1–2 shifts

Data acquisition rate:

2–5 min/data point + 100 percent extra time for wind-off images

Typical PSP accuracy in  $C_p$ :

0.1–0.15 for  $M = 0.2$  and 0.2 for  $M = 0.1$

Notes:

This is a good facility for PSP work at low speeds ( $M = 0.1$ ). Optical access is very good for semispan and vertically mounted models and for the upper surface of horizontal models. Optical access for the lower surface of horizontally mounted models is poor.

#### 2.2.4.4. Application in Ames 40 × 80 ft Wind Tunnel

Status:

Implementation

Downtime for PSP application:

2 shifts (estimate)

Data acquisition rate:

5 min/data point + 100 percent extra time for wind-off images (estimate)

Typical PSP accuracy in  $C_p$ :

0.2 for  $M = 0.2$  (estimate)

Notes:

PSP was used in this facility before refurbishment, but acoustic modifications to the test section since then have severely restricted optical access. PSP capability will depend on the construction of in-tunnel pods to hold lamps closer to the model or the use of special projection lamps. PSP application to the large models used by the 40 × 80 ft tunnel will be time-consuming. Large translucent panels installed in the contraction and diffuser sections of this tunnel admit sunlight, making it difficult to use PSP during daylight hours.

#### 2.2.4.5. Application in Ames 80 × 120 ft Wind Tunnel

Status:

No PSP work planned

Notes:

PSP testing would be quite difficult in this facility because of the large size of the test section, low maximum flow speed, and natural light entry into the test section.

#### 2.2.4.6. Application in Ames 11 ft Transonic Wind Tunnel

Status:

Implementation

Downtime for PSP application:

1–2 shifts (estimate)

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical PSP accuracy in  $C_p$ :

0.02 at transonic speeds (estimate)

Notes:

PSP was used six times in this facility before refurbishment with good to excellent results. Optical access is fairly good from all sides.

*2.2.4.7. Application in Ames 9 × 7 ft Supersonic Wind Tunnel*

Status:

Implementation

Downtime for PSP application:

1–2 shifts (estimate)

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical PSP accuracy in  $C_p$ :

0.02 at transonic and supersonic speeds (estimate)

Notes:

PSP was used four times in this facility before refurbishment with fair to good results. Optical access is fairly good from the sides but poor from top and bottom. Problems using PSP include condensation at some Mach–stagnation-pressure combinations (although the refurbishment should improve this). PSP tests in this facility should include paint-on–paint-off flow intrusiveness checks.

*2.2.4.8. Application in AEDC Transonic 16T Wind Tunnel*

Status:

Operational

Downtime for PSP application:

1–2 shifts

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images

Typical PSP accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Fully automated eight-camera system allows very good optical access from all sides.

*2.2.4.9. Application in AEDC Transonic 4T Wind Tunnel*

Status:

Planned

Downtime for PSP application:

1 shift

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images

Typical PSP accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Optical access is fairly good from all sides.

*2.2.4.10. Application in AEDC Tunnel A*

Status:

Operational (dedicated system)

Downtime for PSP application:

1 shift

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images

Typical PSP accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Optical access is very good from the sides, fair to poor from top and bottom.

#### *2.2.4.11. Application in Langley Low-Turbulence Pressure Tunnel*

Status:

No dedicated system available; however tests can be set up on a case-by-case basis

Downtime for application:

1 shift

Data acquisition rate:

5–10 sec/data point + 100 percent extra time for wind-off images

Typical accuracy in  $C_p$ :

0.2

Notes:

Optical access is fair. PSP tests in this facility should include paint-on–paint-off flow intrusiveness checks.

#### *2.2.4.12. Application in Langley 14- by 22-Foot Subsonic Tunnel*

Status:

No dedicated system available; however tests can be set up on a case-by-case basis

Downtime for application:

1 shift

Data acquisition rate:

5–10 sec/data point + 100 percent extra time for wind-off images

Typical accuracy in  $C_p$ :

0.2

Notes:

Optical access is fairly good from all sides. PSP tests in this facility should include paint-on–paint-off flow intrusiveness checks.

#### *2.2.4.13. Application in Langley 16-Foot Transonic Tunnel*

Status:

Operational (dedicated system)

Downtime for application:

Less than 1 shift

Data acquisition rate:

5–10 sec/data point + 100 percent extra time for wind-off images

Typical accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Optical access is fair. A two-camera system is available with both mounted in the ceiling. UV lights (up to 12) are used to illuminate the model. PSP tests in this facility should include paint-on–paint-off flow intrusiveness checks.



#### 2.2.4.14. Application in National Transonic Facility

Status:

Planned (see section 2.2.5)

Downtime for application:

1 shift

Data acquisition rate:

5–10 sec/data point + 100 percent extra time for wind-off images

Typical accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Optical access is fair. Two cameras are available for overhead (ceiling or floor application) and one in the sidewall. Illumination is accomplished with flashlamps.

#### 2.2.4.15. Application in Langley Unitary Plan Wind Tunnel

Status:

Operational (dedicated system)

Downtime for PSP application:

Less than 1 shift

Data acquisition rate:

5–10 sec/data point + 100 percent extra time for wind-off images

Typical accuracy in  $C_p$ :

0.03 at transonic speeds

Notes:

Optical access is fairly good from both sides. Model must be rotated  $90^\circ$  for testing. PSP tests in this

facility should include paint-on–paint-off flow intrusiveness checks. PSP has been applied in UPWT low Mach number and high Mach number test sections to obtain global surface static pressure mapping and flow visualization on selected airplane models at supersonic speeds. Several PSP chemistries based on formulations from the University of Washington, Ames Research Center, and Langley Research Center have been successfully implemented, and an example of a false-colored PSP image of a generic delta wing configuration tested in the low Mach number test section of UPWT is shown in figure 10. The acquisition of PSP images is done simultaneously with the measurement of the model surface static pressures at numerous discrete locations using an ESP system. The ESP tap data are instrumental to the in-situ calibration of the PSP images. The ESP modules are mounted internally to the model and are configured with purge air lines to prevent contamination of the pressure orifices during the paint application. Preparation for PSP testing requires approximately 1 shift, and includes the separate application and curing of a Krylon white base coat and the special luminescent paint to the model surface area of interest. Registration marks are applied at several locations on the model surface after the paint has fully cured. The model is rolled  $\pm 90^\circ$  to provide the required optical access for high-resolution scientific-grade digital cameras. These special liquid-cooled

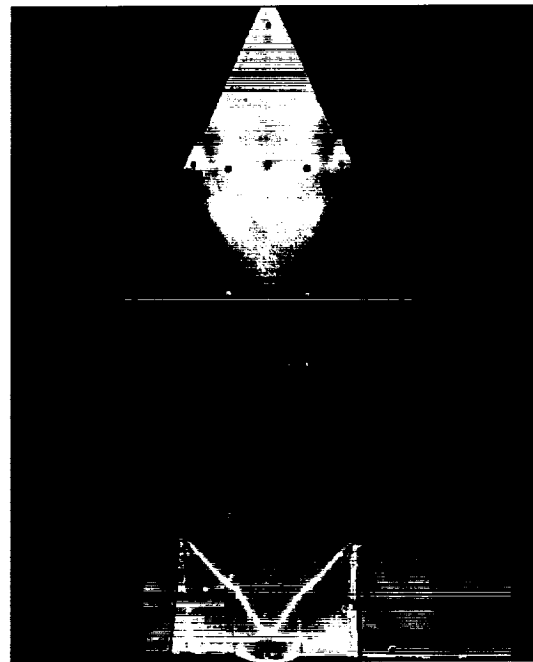


Figure 10. False-colored PSP image of generic delta wing configuration in UPWT.

cameras are mounted in the webbing of the test section sidewall which, in turn, is sealed by a lighttight, "walk-in" enclosure. The cameras are remotely controlled via SGI and PC computer workstations, and all image files are subsequently stored on optical disks for off-line processing. Excitation of the PSP is provided by continuous ultraviolet lights that are also mounted in the webbing of the test section sidewall. Several wind-off and wind-on images are acquired at selected angles of attack and Mach number. Exposure of the PSP to the UV illumination is limited as much as possible to avoid the adverse effects of photodegradation. Postprocessing of the PSP images is conducted on an SGI platform using a software package developed by the Ames Research Center. Approximately 1 shift is required to provide a limited transmittal of final results. These results are typically presented in the form of composite plots showing the false-colored images, comparisons of the PSP and ESP static pressure distributions, and detailed PSP pressure distributions at selected chordwise and streamwise stations on the model surface.

## 2.2.5. Temperature Sensitive Paint

*Clifford J. Ohara*  
*NASA Langley Research Center*

TSP (refs.1 and 9) is a quantitative surface technique and is similar to PSP but the paint chemistry is sensitive to temperature rather than oxygen partial pressure. TSPs are commonly used to detect boundary-layer transition; this is accomplished by generating a temperature difference between the model and the flow. Because the turbulent boundary layer convects heat more efficiently than the laminar boundary layer, the transition region is marked by a surface temperature change. Note that TSP detects transition in the same manner as IR thermography.

The TSP paint is capable of showing boundary-layer transition as well as shock location over the entire model surface. The model is coated with a special fluorescent paint whose brightness changes with varying temperature. The model is illuminated with blue lights to excite the paint. The resulting emission from the paint is recorded by using scientific CCD cameras. In order to detect the subtle differences often occurring between a laminar and a turbulent boundary layer, the tunnel temperature is varied over the test

run. Successive images are acquired while the tunnel temperature is changing. The amount of temperature change can vary based on the other test conditions; however, a 5°F change is often enough to detect the state of the boundary layer. Problems with this technique include large model down time for paint applications and low data rates.

The requirement to change tunnel temperature in order to obtain transition data means that TSP can only be used for this purpose in temperature-controlled tunnels. Many of the facilities discussed have this capability. Using TSP for transition detection in non-temperature-controlled facilities may be possible if the model can be heated or cooled prior to a run. Even without model heating or cooling, TSP can still be used in these tunnels to get an indication of temperature variation on a model.

### 2.2.5.1. Application in Ames 12 ft Pressure Wind Tunnel

Status:

Operational

Downtime for TSP application:

1 shift

Data acquisition rate:

7 sec/data point + 100 percent extra time for reference images

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

For TSP studies in the 12 ft Tunnel, a paint consisting of EuTTA (europium (III) Thenoyltrifluoroacetate, formula:  $(C_8H_4O_2SF_3)_3Eu$ ) in model airplane dope is applied over a base coat of white Krylon or RPM Rust-Oleum enamel. To obtain TSP data, the tunnel radiator is turned off and the tunnel is allowed to heat to about 80°-85°F, which takes about 15-20 min. A set of reference images is taken at the same model angles where transition data are to be

obtained. Then the radiator is turned back on and the tunnel cooled at the maximum rate. Good transition images can be obtained for about 3 min during cooling. The 12 ft TSP system uses flash illumination. The same system can be used to take minituft data as well.

#### *2.2.5.2. Application in Ames 11 ft Transonic Wind Tunnel*

Status:

Planned

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

#### *2.2.5.3. Application in Ames 9 × 7 ft Supersonic Wind Tunnel*

Status:

Planned

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

#### *2.2.5.4. Application in AEDC Transonic 16T Wind Tunnel*

Status:

Planned

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

#### *2.2.5.5. Application in Langley Low-Turbulence Pressure Tunnel*

Status:

No dedicated system, however tests can be set up on a case-by-case basis

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

#### *2.2.5.6. Application in Langley 16-Foot Transonic Tunnel*

Status:

Operational (dedicated system)

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

#### *2.2.5.7. Application in National Transonic Facility*

Status:

Planned (expected by 12/01/01)

Downtime for application:

1 shift

Data acquisition rate:

5–10 sec/data point + 25 percent extra time for wind-off images

Typical TSP accuracy:

1- to 2-percent chord location

Notes:

Optical access is fair. Two cameras for overhead (ceiling or floor application) and one in the sidewall will be available. Illumination is accomplished with flashlamps.

#### *2.2.5.8. Application in Langley Unitary Plan Wind Tunnel*

Status:

Operational (dedicated system)

Downtime for TSP application:

1 shift (estimate)

Data acquisition rate:

7–10 sec/data point + 25 percent extra time for wind-off images (estimate)

Typical TSP accuracy:

2- to 3-percent chord location (estimate)

Notes:

TSP data have not been obtained in this facility, but the PSP system is capable of obtaining TSP data.

## **2.3. Off Surface Techniques**

### **2.3.1. Laser Vapor Screen**

*Gary E. Erickson*  
*NASA Langley Research Center*

The laser vapor screen technique (ref. 1) is qualitative and primarily used to identify off-surface flow features, such as shocks and vortices. The vapor screen makes visible these flow features through the introduction of a vapor, such as water, and then the cross-section illumination of a laser sheet. These images are then recorded for analysis.

### 2.3.1.1. Application in Langley Unitary Plan Wind Tunnel

The laser vapor screen technique is applied in the low Mach number and high Mach number test sections of UPWT to visualize the cross-flow patterns about airplane, missile, and spacecraft models at supersonic speeds. Features that are typically revealed include vortical flows, shock waves, and the interaction of these flow phenomena. Water is injected into the tunnel circuit in sufficient quantity to create condensation in the test section, and the flow phenomena of interest about the model are generally revealed as dark regions that lack condensate. The cross-flow patterns are illuminated by an intense sheet of light produced by an ion-argon laser operating in a continuous, all-lines, multimode configuration. An example of a laser light-sheet flow pattern obtained at UPWT is shown in figure 11. The laser system consists of a laser head and power supply and fiber-optic components that refocus and direct the laser beam to an optics package that generates a thin sheet of light of controllable thickness and spread angle. The light-sheet optical package is secured to the test section sidewall and remains fixed during the flow-visualization runs. The flow patterns at different model longitudinal stations are observed by forward and aft traversal of the model support mechanism. A flat paint is uniformly applied to the



Figure 11. Example of laser light-sheet flow pattern.

model and sting to reduce the flaring effects when the laser light impinges the metal surfaces. Observation and documentation of the flow patterns are accomplished with a 70-mm Hasselblad camera and a miniature color or black-and-white video camera, which are mounted in the test section in protective enclosures. Alternatively, mirrors may be installed in the webbing of the test section sidewall to allow viewing and recording of the vapor screen patterns with an externally positioned video camera. Proper control of the water injection allows extended vapor screen runs for ranges of angle of attack, sideslip, and Mach number.

### 2.3.2. Schlieren

*John R. Micol and Floyd J. Wilcox, Jr.  
NASA Langley Research Center*

The schlieren technique (ref. 1) is off surface and qualitative and is primarily used to observe the shock waves generated by and around a wind-tunnel model and the associated reflections off the tunnel walls.

#### 2.3.2.1. Application in Langley Unitary Plan Wind Tunnel

Each test section of the UPWT is equipped with a single-pass, off-axis schlieren system. A schematic of the system is shown in figure 12. The complete schlieren system consists of a light source, two spherical mirrors, knife edge, optical beam splitter, still camera, flat mirror, video camera, and image screen. The entire system is supported from a beam as a unit and can be positioned along the longitudinal axis of the test section to provide schlieren images of any part of the test section. The light source is provided by a xenon vapor arc lamp that is operated continuously. An optical beam splitter is located just behind the knife edge and is used to provide a schlieren image for both the still and video cameras. The still photographic images are recorded with a 70-mm Hasselblad camera that is equipped with an annotation device which records such items as the run number, point number, Mach number from the data acquisition system on the negative for each photograph. A typical schlieren photograph is shown in figure 13 (vertical black lines in photograph are test section window support bars).

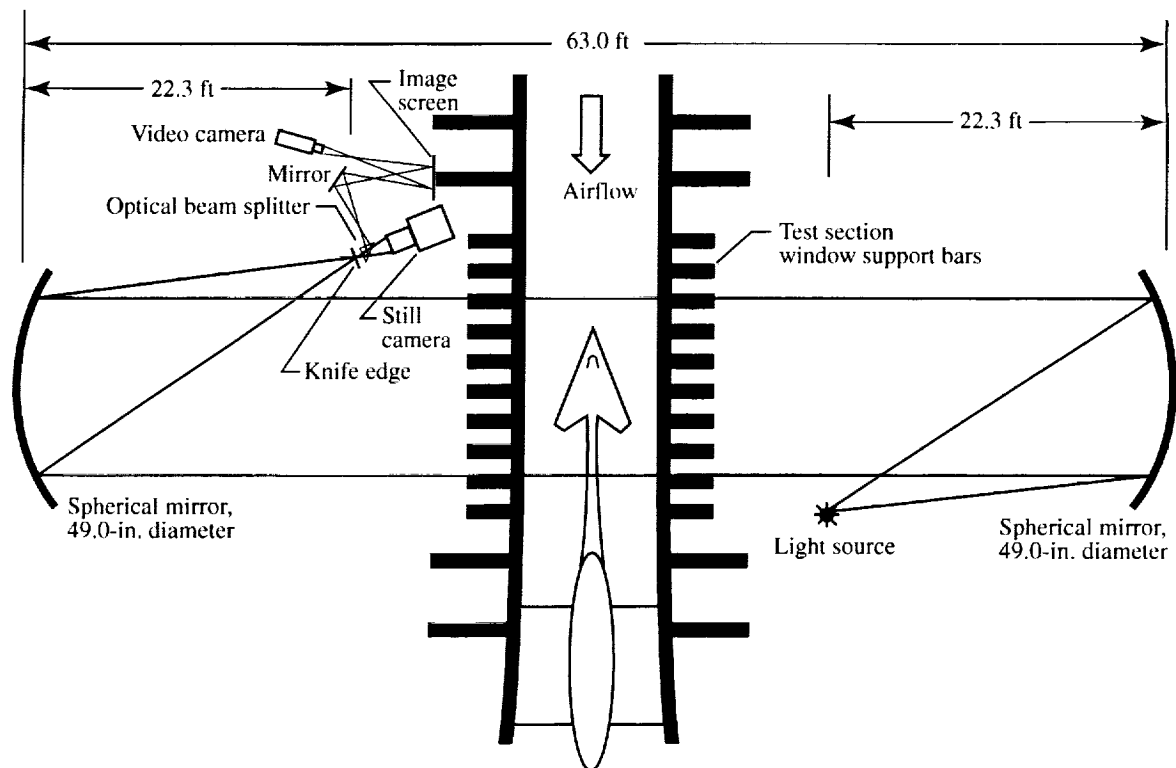


Figure 12. Schematic of schlieren system.

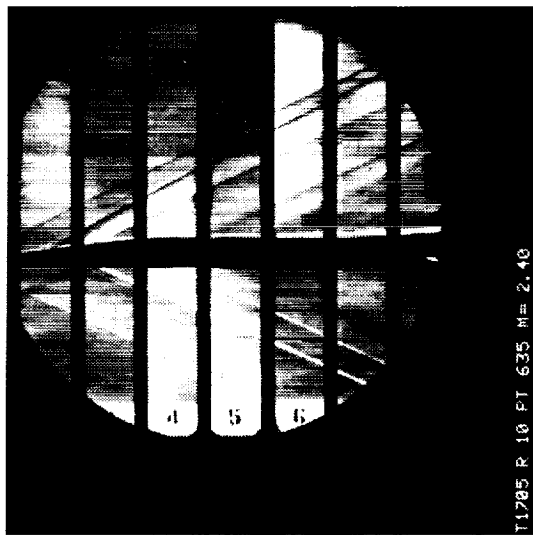


Figure 13. Typical schlieren photograph of a High-Speed Research airplane model.

Output from the video camera is supplied to a video cassette recorder used to record schlieren movies. A title generator is used to annotate the image so that such items as run number, point number, Mach number may be recorded. This video camera output

including the annotation is also supplied to a PC having frame-grabber capability. MPEG files are generated and downloaded to the HSR Adapt Website providing wide distribution of the flow-visualization images. Exposed film (70 mm, ISO 400, TriX) from the Hasselblad camera is processed and 8- by 10-in. B&W photographs are made. The photographs are scanned via a high-resolution digital scanner. These digital images are then manipulated using off-the-shelf software to achieve greater detail for analyzing shock shapes observed in the flow field.

### 2.3.3. Shadowgraph

*John R. Micol and Floyd J. Wilcox, Jr.*  
*NASA Langley Research Center*

The shadowgraph technique (ref. 1) is also off surface and qualitative and is primarily used to observe the shock waves generated by and around the model. It is a simpler system than the schlieren, that is, can be thought of as a subset, and can sometimes be used when the schlieren is not available or its operation not accommodated in a test facility.

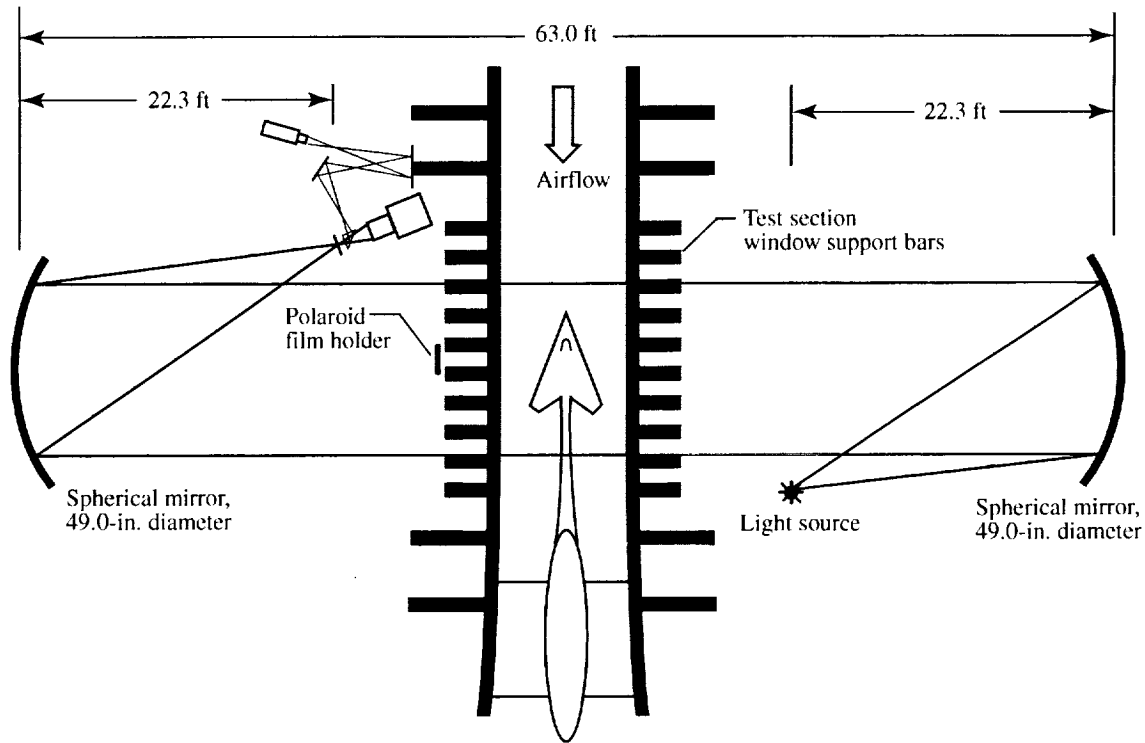


Figure 14. Schematic of shadowgraph system.

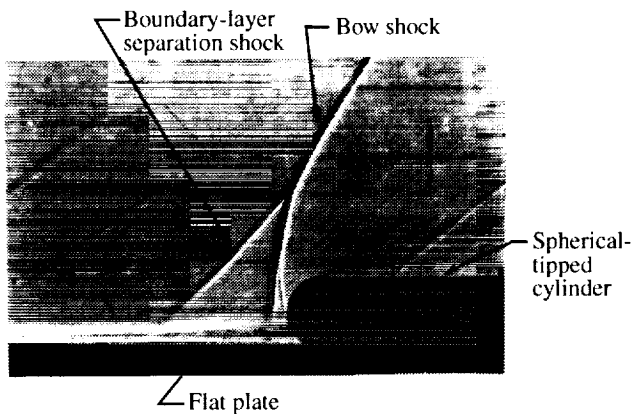


Figure 15. Typical shadowgraph images showing spherical-tipped cylinder mounted on flat plate.

#### 2.3.3.1. Application in Langley Unitary Plan Wind Tunnel

Shadowgraphs are obtained with the same schlieren system described in section 2.3.2 except that the light source is operated in a flash mode rather than a continuous mode. A Polaroid film holder is placed

between the test section window support bars at the location of interest as shown in figure 14. The lights in the test section are turned off, the Polaroid film (Type 57, ISO 3000, high speed 4 by 5 in.) is uncovered, and the light source is flashed which exposes the film. Only a small area of the test section, the size of the Polaroid film (approximately 4.5 in. by 3.5 in.), can be captured in a shadowgraph. A typical shadowgraph is shown in figure 15.

Like photographs obtained with the Hasselblad camera, the Polaroid photographs are scanned via a high-resolution digital scanner. These digital images are then manipulated by using off-the-shelf software to achieve greater detail for analyzing shock shapes observed in the flow field.

#### 2.3.3.2. Application in Langley 16-Foot Transonic Tunnel

The same technique used in UPWT has been applied in the 16FTT tunnel as well.

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